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# Use of Recycled Aggregates in Lime Mortars for Conservation of Historical Buildings

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**Abstract:** The use of recycled burnt clay brick sand (RBS) and recycled concrete sand (RCS) in historical lime-based repair mortars can reduce the environmental impact caused by construction and demolition waste disposal. This study examined the use of fine recycled concrete and recycled brick aggregates for the production of historical repair mortars using hydraulic lime binder and the influence of the resulting mortars on the performance of historical buildings in reduced scale walls (stacks). Natural-river-sand mortar (NSM) was used as control. Results showed that the recycled-burnt-brick-sand mortar (RBSM) performed better in terms of strength compared to the recycled-concrete sand (RCSM) and the NSM mortars. At the age of 7 and 28 days, the flexural strength of the RBSM and the RCSM was 131% and 44%, respectively, and 300% and 68% above that of the control mortar. The 45-day flexural strength of the NSM and RCSM was similar whilst the RBSM mortar's strength was 177% higher. The compressive strength followed similar trend. On the other hand, the strength and modulus of elasticity of the stacks were found to be largely influenced by the strength of the brick units.

**Keywords:** conservation; hydraulic lime; recycled-burnt-brick sand; recycled-concrete sand; historical mortar; mechanical properties

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## 1. Introduction

The use of fine recycled aggregates in cement mortars for restoration of buildings has been studied in the past years. The properties of mortars prepared with recycled aggregates (RAs) vary depending on the type and abundance of crystalline phases in the recycled material. Mortars rich in concrete and natural stones show different mechanical performance compared to those prepared with recycled clay-based materials such as bricks and tiles [1–3].

When used in concrete or cement mortar, recycled aggregates can form materials of lower mechanical performance. For recycled concrete aggregates, porosity caused by the interfacial transition zone between the adhered cement paste and mortar on the aggregates [1–3] and microcracks formed during the production of the aggregates are the main factors for their inferior properties. Fine aggregates, particularly the finer fraction, <2.0 mm [4], contain more mortar and cement paste than the coarser fraction of recycled concrete aggregates. Also, the elongated, angular and irregular shapes of the aggregates, which are mainly influenced by the production methods, affect the resulting properties of the concrete or mortar. These lead to a high void content, surface area and inter-particle

friction between particles and when mixed, cause a high water demand, poor workability, low strength and highly permeable mortar [1,5]. The poor quality of the aggregates is also inherent from the parent concrete [6]. However, if treated by, for example, pre-wetting with water [5,7] or compensated for water absorption by adding water during mixing [8], the properties are improved. Moreover, recycled-burnt-brick sand may undergo pozzolanic reactions and improve the strength of mortars [3]. The pozzolanicity of recycled-burnt-brick sand increases with an increase in its specific surface area [9–11].

Huang et al. [10] examined cement mortars with crushed dry and pre-soaked waste clay brick aggregates (WCB) replacing natural sand in different levels of replacement (0, 25, 50, 75, and 100 wt%) and curing conditions, i.e., standard and air curing. It was concluded that mechanical properties and water absorption increased with replacement levels in mixes with dry WCB, but the properties deteriorated where pre-soaked WCB was used, due to formation of extra hydration products from the pozzolanic reactions and well-refined porosity and interfacial transition zone, which outweighed the porosity of the WCB materials. For mortars with pre-soaked materials, an increase in water above the effective w/b ratio increased the porosity of the matrix. Mortars cured under standard conditions performed better than air-cured materials.

Yue and Wang [11] reviewed the application of ceramic-added air lime and cement mortars in buildings. The study indicated that the addition of ceramic powders in air-lime hydraulic lime significantly improved the compressive and flexural strengths of mortars when compared with plain binders. This improvement was attributed to the synergetic effect of the pozzolanic nature of the powders and their filler effect. The formation of calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H) when lime reacts with the amorphous phases of ceramic materials like brick powder refines the pore structure, enhances cohesion (bond) at the interfacial transition zone (ITZ), and improve compactness and strength.

Böke et al. [12] characterised mortars, plasters and bricks used in construction of Ottoman bath buildings. Mortars and plasters were reported to have a compressive strength >10 MPa and a density and porosity of ca. 1.7 g/cm$^3$ and 38%, respectively. Bricks had a density between 1.7 and 1.8 g/cm$^3$ and a porosity between 33 and 37%. Both mortars and plasters were identified to be brick–lime materials with evidence of amorphous phases.

Raini et al. [13] examined the use of concrete and brick waste as sustainable alternatives in air-lime mortar. The mixes studied were composed of an air-lime binder partially replaced with 30% brick powder and blended fine sand, i.e., natural sand replaced with recycled aggregates in levels 0, 20, 40, and 60 wt.%. The control mortar contained the air lime and natural aggregates only. While the mechanical properties deteriorated with the increased replacement of the recycled concrete aggregates, the durability performance, i.e., water absorption and porosity, improved. The decay of the mechanical properties was attributed to the porous nature of the interfacial transition zones due to the porous adhered cement mortar on surfaces of the aggregates. According to the study [13], improvement in durability performance was due to the compact microstructure resulting from the pozzolanic reaction between lime and the amorphous phase of the brick powder.

On the other hand, masonry mortar does not require a very high strength but rather enough flexibility and permeability to drain water from the units. As a case in point, the strength and porosity of old mortars in Greece ranged between 1 and 6 MPa and between 20 and 35% [14], respectively.

Ancient lime mortars are weak and poorly set in high humid environment apart from those that were mixed with additives [15–17]. As a result, there came a need for higher early-strength development which is normally provided by fast-setting materials that are characterised by hydraulic behaviour. Natural hydraulic lime sets fast and forms mixes

with improved mechanical properties in humid environments. The lime is compatible with historical binders, and it is therefore suitable for the repair of historic buildings [7,18,19]. However, other important constituent of mortars should be considered, including aggregates, since the type and nature of the aggregates affect the engineering properties of mortars [20,21]. Generally, mortars for historic building repairs consist of hydraulic lime, water and fine sand. The scarcity of sand for construction, which is a non-renewable resource, brings the need for the exploration of alternatives and the reuse of materials [6,22]. With a hydraulic lime binder, some burnt clayey construction and demolition wastes in the presence of water undergo pozzolanic reactions forming hydration products responsible for the strength of mortar [20,23,24].

On the other hand, the repair of historical constructions requires that a large part of the architectural, structural and historical texture of the building be conserved. The minimum intervention principle is applied to enable as much preservation as possible [25]. For this reason, the repair mortar should respect the authenticity of the original material and the structure in terms of compatibility [26] and should be chosen such that it is easily repairable in case of later damages [25,27]. Although cement mortar has been found to have a high structural strength, it is not considered compatible [28,29]. Removal of the damaged cement mortar would damage the substrate of the masonry units causing more damage to the structure [13].

Several studies have been conducted to examine the influence of partially replacing natural sand with recycled concrete and other fine sands in cement mortars [5]. However, there is a dearth of literature existing on mortars with recycled-concrete aggregates and lime-based binders, particularly for the repair of historical constructions. This study presents the mechanical performance of historical hydraulic lime mortars with recycled concrete and brick sands in comparison to the natural-sand mortar.

## 2. Materials and Methods

### *2.1. Materials*

Hydraulic lime type NHL-3.5 produced and distributed by a Spanish company, Cemento Natural Tigre, was used as a binder in this study. The lime had a compacted bulk density of 660 kg/m$^3$ and conformed to EN 459-1 [30]. The lime consisted of mainly calcite ($CaCO_3$), portlandite ($Ca(OH)_2$), quartz ($SiO_2$), larnite ($Ca_2SiO_4$) and a small quantity of lime (CaO). The fine aggregates used in this study (Figure 1) were of three types: natural river sand (NS), recycled-concrete sand (RCS) and recycled-brick sand (RBS). The natural sand was collected from a natural-aggregate quarry, located in Cataluña, Spain, and was used for the production of the control mortar. The recycled-concrete sand as well as the brick sand was procured from a construction and demolition recovery plant, also located in Cataluña, Spain. The NS, RCS and RBS had similar mineralogical composition with mainly quartz ($SiO_2$), calcite ($CaCO_3$), albite ($NaAlSi_3O_8$), microcline ($KAlSi_3O_8$), chamosite ($(Fe^{2+},Mg)_5Al(AlSi_3O_{10})(OH)_8$), mica ($Al_2K_2O_6Si$), and dolomite ($CaMg(CO_3)_2$). The XRD diffractograms for the materials are available on request. The sands were sieved to remove all particles greater than 2 mm and the amounts of fines were adjusted to between 5% and 9%. The particle size distribution of the sands is shown in Figure 2. Burnt bricks used for the study to establish the properties of historical masonry units and walls against the resulting conservation mortars were produced by Cerámica Piera S. L (Catalan company). The physical properties of the materials are shown in Table 1.



(**a**) (**b**) (**c**)

**Figure 1.** Fine aggregates used for the study: (**a**) natural sand, NS (**b**) recycled-concrete sand, RCS and (**c**) recycled-burnt-brick sand, RBS.

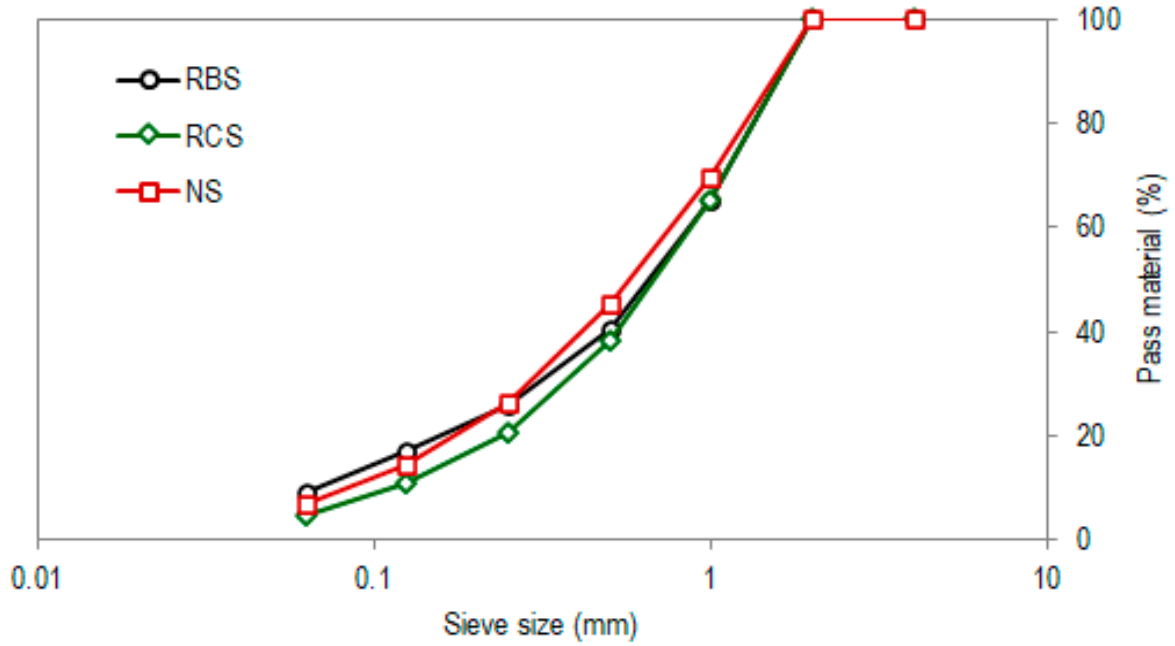



**Figure 2.** Particle size distribution of fine aggregates.

**Table 1.** Physical properties of the materials.

| Property | Units | Brick 1 | Brick 2 | Lime | NS | RCS | RBS |
|---|---|---|---|---|---|---|---|
| Apparent density | g/cm$^3$ | 2.61 | 2.55 | 2.53 | 2.68 | 2.65 | 2.70 |
| Dry density | g/cm$^3$ | 1.82 | 1.81 | - | 2.60 | 2.08 | 2.08 |
| Surface saturated density | g/cm$^3$ | - | - | - | 2.63 | 2.30 | 2.31 |
| Loose density | g/cm$^3$ | - | - | 0.60 | 1.54 | 1.18 | 1.18 |
| Compacted density | g/cm$^3$ | - | - | 0.66 | 1.65 | 1.25 | 1.28 |
| Water absorption | % | 16.6 | 16.1 | - | 1.1 | 10.3 | 10.7 |
| Vol of pores | % | 30.2 | 29.0 | - | - | - | - |
| Aggregate index, AI | - | - | - | - | 17.1 | 9.2 | 18.5 |

### 2.2. Methods

#### 2.2.1. Characterisation of Materials

The mineralogical composition of the materials was established by X-ray diffraction in powder samples, with a Bruker D8-A25 Diffractometer (manufactured by Bruker Corporation, Billerica, MA, USA). The equipment was used with a Cu X-ray source (CuKa radiation, 40 kV and 40 mA working conditions). All scans were acquired between 4° 2theta and 80° 2theta with a step size of 0.017° and a counting time of 0.8 s per step. Phase identification was carried out using the DIFFRAC EVA 4.0 software in conjunction with the ICDD PDF-2 database and the Crystallography Open Database (COD)

The particle size distribution was carried out based on ASTM D422-63 [31]. Aggregate indexes, which describe the quantity of fines and the form of the particle distribution curve from the smallest grains to the largest were determined following the method explained by Konow [32], where higher indexes are indicators of fine materials and improved properties of the resulting mortars [32]. The bulk density of the binder and aggregates was determined using CPC 14.2 of the RILEM TC [33] method. The apparent, dry and surface-saturated dry density, water absorption and porosity of the fine aggregates were determined using a pycnometer according to the UNE-EN [34] standard.

#### 2.2.2. Mix Design, Sample Preparation and Fresh State Properties of the Mortars and Stack Walls

Mortars were prepared by mixing surface-saturated dry sands to a ratio of 1:2.5:0.8 by volume of natural hydraulic lime (NHL) binder, aggregates and water, respectively, using a mortar mixer machine running for 255 s for each mix. Fresh mortar was tested for workability using a table flow according to ASTM C1437-12 [35], water retention according to ASTM C1506-03 [36], air content according to ASTM C231 [37] and fresh density tested per CPC 10.1 of RILEM TC [38].

The mortars were cast in metallic moulds to form 40 × 40 × 160 mm specimens that were used for various tests. The specimens in moulds were cured in moist condition in a humidity chamber conditioned at 20 °C and average relative humidity of about 95%. As a result of the low early-strength development of hydraulic lime mortars, the specimens were demoulded after three days from casting as per section A.6.2 of LUMA A6 of RILEM TC [39] recommendations and left in the humidity chamber for further curing. The mix design for the production of three prisms is shown in Table 2.

**Table 2.** Composition of mortar for one 3-gang, 40 × 40 × 160 mm prism mould.

| Material | Volume | Weight (g) | | |
|---|---|---|---|---|
| Lime | 1 | 236 | 236 | 236 |
| Sand | 2.5 | 1450 **(NS)** | 1203 **(RCS)** | 1080 **(RBS)** |
| Water | 0.8 | 320 | 320 | 320 |

The reduced scale masonry walls made of three layers of burnt bricks were prepared on a hard flat floor surface following clause B.1.2 of LUMB B1 [40] recommendations. The walls were cured in plastic bags for 28 days in a room with an average temperature of about 23 °C before testing. Three stack-bonded prisms of three courses each of half–cut bricks bedded on about 10 mm thick mortar and with dimensions of 140 × 150 × 160 mm were used for compressive strength testing, with two being used for the secant modulus test prior to testing for compression. The compressive strength of the stacks was determined according to the standard LUMB B1 of RILEM TC [40] coupled with methods explained by Peverini [41] and Pelà et al. [42]. The load was applied at a rate of 50 N/s

and 0.008 mm/s for the compression and the modulus of elasticity test, respectively. The tests were performed to study the influence of the recycled fine aggregate in mortars to the behaviour of the masonry walls under compression loads. The top and bottom faces of the walls in contact with the platens of the testing machine were polished to improve the contact between the specimen under test and the platens and to avoid stress concentration.

#### 2.2.3. Compressive Strength, Flexural Strength and Modulus of Elasticity of Bricks and Mortar

The compressive strength of two randomly sampled bricks was established using two 40 mm cubes (Figure 3) prepared from the selected bricks. Two prisms with 40 × 40 × 160 mm dimensions were also prepared and first used for the determination of the modulus of elasticity and later for flexural strength. After the flexural strength test, the two halves from each of the two specimens were also used for the determination of the compressive strength as per LUM A1, RILEM TC [43]. For the compression test, the load was applied at 50 N/s. The flexural strength test was conducted according to LUM A2 [44] with the load applied at the rate of 10 N/s. The modulus of elasticity of the bricks was determined as the average slope of the last three of the four cycles of loading–strain curves when the specimens were subjected to a maximum load equal to one third of the compressive strength of the brick as per RILEM TC, CPC 8 [45]. For the modulus of elasticity measurements, the load was applied at the rate of 0.008 mm/s.




(**a**) (**b**)

**Figure 3.** (**a**) Preparation bricks (facing), (**b**) 40 mm brick cubes for various tests.

RILEM TC, LUM A7 [46] recommendations were used to determine the flexural strength of mortars. Three 40 × 40 × 160 mm specimens for each type of mortar were used for this purpose. Four halves formed after the flexural strength test of mortars were used for establishing the compressive strength following the LUM A6 of RILEM TC [39]. However, a modification was made to adopt the loading rate used during the determination of the strength of the brick units. The tests for each specimen of the respective mortar were performed at the age of 7, 28 and 45 days.

## 3. Results

### *3.1. Density, Porosity, Water Absorption and Aggregate Index of the Materials*

The physical properties of the materials are shown in Table 1. Based on aggregate indexes (AIs) and the particle distribution curves (Figure 2), NS and RBS were relatively

finer than RCS. The natural sand was denser than recycled-aggregate sands. The water absorption capacity of the recycled-concrete and brick sands were similar and about ten times higher than that of the natural sand. The higher porosity of the recycled aggregates accounted for both their lower densities and higher water absorption capacity. The high porosity in recycled-brick sand could be a function of the recycling process adopted; whereas for the recycled-concrete sand, it was a result of the existence of a porous cement paste between the aggregates and the cement matrix, i.e., the interfacial transition zone [2,5]. On the other hand, the bricks were found to be equally dense. However, the porosity and water absorption of Brick 1 was higher than that of Brick 2. The corresponding difference in porosity and water absorption was about 4.1% and 3.2%, respectively. The dissimilarity in the properties of such historical brick units might have been caused by variability in production process or the units belonging to different production periods [43].

### *3.2. Fresh Properties of Mortars*

Water retention capacity of all the three mortars was found to be practically the same. The recycled concrete and brick sand mortars showed about 1% and 5%, respectively, less water holding capacity than the natural aggregates. The values presented in Table 3 are only for comparison purpose as the suction pressure employed during the test (14 kPa for 30 s) was much higher than the standard specified pressure (7 kPa for 60 s). The amount of air in all three mortars was also similar, implying similar workability conditions as indicated by the table flow results—Figure 4 and Table 3. The slightly higher workability in recycled sand mortars resulted from the water added in materials to create a surface-saturated dry state. The density of the mortar with recycled concrete and brick aggregate was the same, whereas the natural sand mortar was found to be slightly denser.

**Table 3.** Fresh-state properties of mortars.

| Property | Unit | NSM | RCSM | RBSM |
|---|---|---|---|---|
| Table flow | cm | 10.6 | 12.9 | 13.6 |
| Water retention | % | 57.8 | 57.3 | 55.0 |
| Air content | % | 4 | 5 | 4 |
| Fresh density | $g/cm^3$ | 2.03 | 1.83 | 1.82 |



(**a**) (**b**) (**c**)

**Figure 4.** Table flow of mortar (**a**) NSM, (**b**) RCSM and (**c**) RBSM.

### *3.3. Dry Density, Water Absorption and Porosity of Mortars*

As for the fresh-state density, the hardened natural sand mortar was denser than mortars with recycled materials. The dry density of the control mortar slightly increased

with age (Figure 5), while there was no increase in density for mortars with recycled fine sands. At the age of 7 days, the apparent density of natural sand mortar was found to be slightly higher (ca. 1.2%) than that of recycled sand mortars (Figure 5). The density of all mortars increased slowly up to the age of 28 days with the recycled-brick-sand mortar (RBSM) having the highest rate of increase, about 2%, compared to the natural-sand mortar (NSM) (1.2%) and the recycled-concrete-sand mortar (RCSM), with an increase of about 0.4%. After 45 days, the density of recycled-concrete-sand and natural-sand mortars dropped slightly while the density of the mortar with recycled-brick sands remained nearly constant. At that age, recycled-brick and recycled-concrete-sand mortars were +2% and −1.2% denser than the natural sand mortar, respectively. While the density of the recycled sands was similar, see Table 1, the apparent (particle) density of the resulting mortars was different, as seen in Figure 5. The higher density of the RBSM was attributed to the pozzolanic reaction of the clays in burnt bricks with portlandite formed in the mix, forming products that densified the matrix. On the other hand, the dry bulk density of the RCSM and RBSM was similar and lower than that of the NSM due to the higher porosity of the recycled materials.

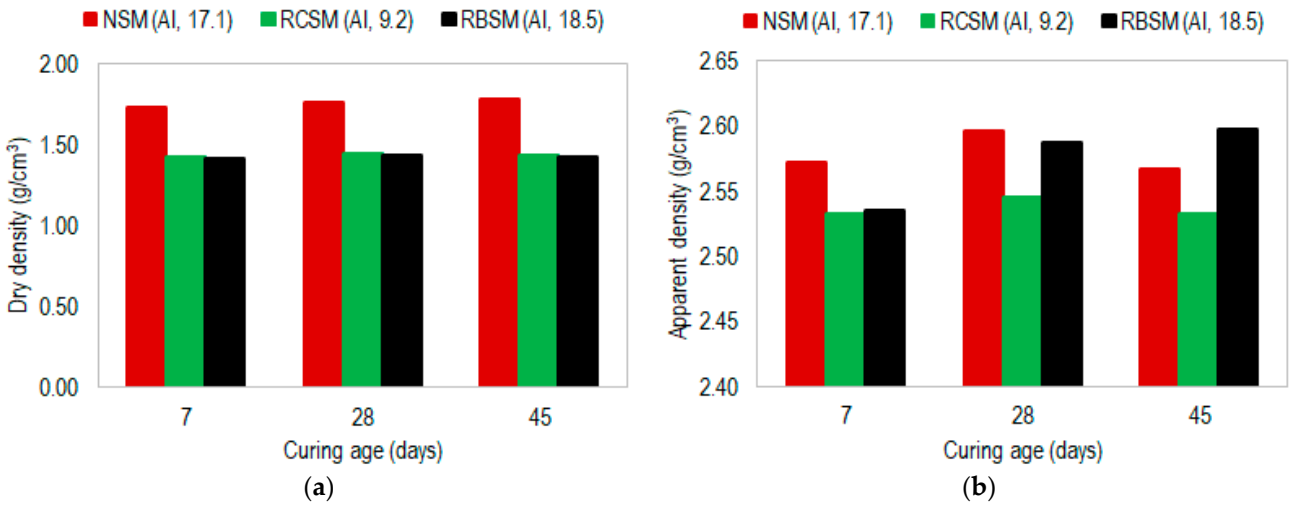



**Figure 5.** (**a**) Dry density and (**b**) apparent density of mortar at different age (Note: results reported are the average of two measurements).

The AI appeared to have no direct influence on the densification of the mortars studied. Although the later-age apparent densities seemed to relate to the AI, the early-age density did not, indicating that the porosity of the materials and the lime-brick sand pozzolanic reactions stated earlier were responsible for the development of the apparent density of mortars.

As expected, mortars containing recycled fine sands had a higher water absorption capacity and porosity than the control mortar, see Figure 6. Over the 45 days of curing, there was no significant change in water absorption (a range of 30–32%) and porosity (between 43 and 45%) for mortars with recycled materials. Both the water absorption capacity and porosity of the control mortar declined slightly with age—from about 19 to 17% and 33 to 31%, respectively. The porosity of both RBSM and RCSM exceeded that of mortars and plasters used in the Ottoman bath buildings reported by Böke et al. [12], which fell between 33 and 37%, but similar to traditional building materials in Cyprus where it ranges between 35 and 40% [11]. The difference in water absorption and porosity of mortars with recycled materials was insignificant. Water absorption and the volume of pores of the mortars (Table 1) correlated with the water absorption of the materials and was independent of the AI of the materials.

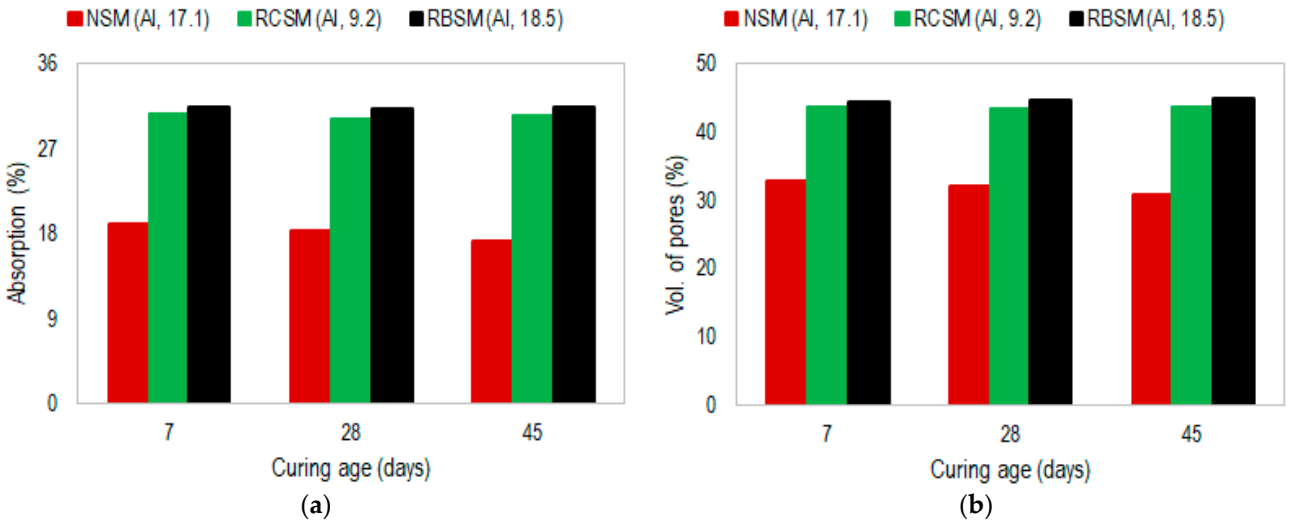



**Figure 6.** (**a**) Water absorption and (**b**) volume of pores of mortars at different ages (Note: results reported are the average of two measurements).

### *3.4. Mechanical Properties of Bricks and Mortar*

The test results showed that the two types of bricks considered in this study had different mechanical properties. The bricks were from the same source and classified into the two types according to their colour. The compressive strength of Brick 2 was about 35.5% higher than that of Brick 1. Similarly, the flexural strength and modulus of elasticity of Brick 2 were 14.9% and 26.9% higher, respectively, than those of Brick 1. The variation in the properties within the same material was also found to be high. For compressive strength, the coefficient of variation was 26% and 19% for Brick 1 and Brick 2, respectively, while the corresponding flexural strengths were 8% and 20%, and the moduli of elasticity were 0.1% and 1.2%, respectively. The higher variation in the properties within the same units was probably caused by the anisotropic behaviour of the material and non-uniform temperature distribution during firing. The differences in the mechanical properties between the historical brick units may be a result of the high variability in production, possible environmental damage depending on the exposure condition of storage, the different age of production or experimental setup conditions [43,47]. The results are shown in Table 4. Using the same batch of bricks, other researchers [41,42] also found variability in compressive strengths and elastic properties.

**Table 4.** Mechanical properties of bricks (mean value ± standard deviation).

| Property | Unit | Material | |
|---|---|---|---|
| | | Brick 1 | Brick 2 |
| Compressive strength | MPa | 22 ± 6 | 30 ± 6 |
| Flexural strength | MPa | 6.5 ± 0.5 | 7.5 ± 1.5 |
| Modulus of elasticity | MPa | 8072 ± 100 | 10,240 ± 119 |

As a result of pozzolanic reactions [20,23,24] of the clays in burnt bricks with the portlandite, the mechanical properties of recycled-brick-sand mortars were exceptionally high except for the high porosity of the recycled brick sand. Although a cement binder was used, Huang et al. [10] associated the performance of cement mortars with the formation of addition hydration products in pozzolanic reactions between crushed-clay-brick aggregates and portlandite formed in the system, the densification of interfacial transition zone and the attendant increase in fracture toughness of the mortars. While Konow [32] indicated that

higher aggregate indexes improved performance of lime-based mortars, the case appears to differ when mortars with different aggregates are compared. The flexural and the compressive strength of natural-river-sand mortar (NSM), recycled-concrete-sand mortar (RCSM), and recycled-burnt-brick-sand mortar (RBSM) are shown in Figure 7, with the aggregate index (AI) shown in the legend. The flexural strength of mortars with recycled sands cured for 7 days was higher than the strength of the control mortar, i.e., the natural-sand mortar. At that age, the RCSM and the RBSM showed 44% and 131% higher strength values, respectively, than the NSM mortar. Similarly, the respective strengths at the age of 28 days were 68% and 300% higher than that of the NSM. After that age, the rate of increase in strength relative to the reference mortar decreased slightly, and after 45 days, the flexural strength of the RCSM and RBSM was higher than that of the NSM by about 3% and 177%, respectively.

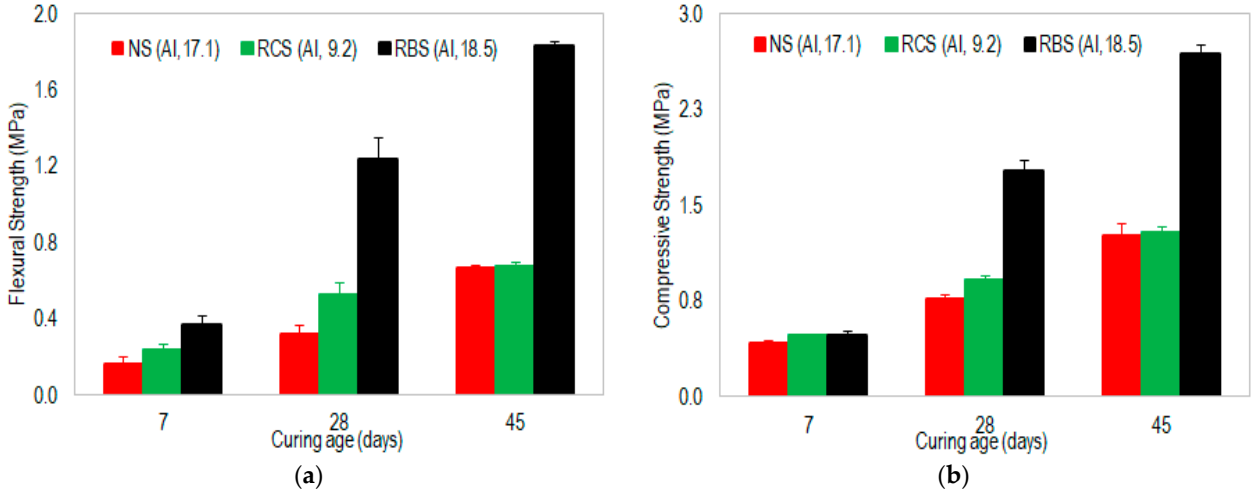



**Figure 7.** Development of (**a**) flexural and (**b**) compressive strengths of mortar with age for different materials.

The compressive strength followed similar trend. The fractional increase in strengths of the RCSM and RBSM with respect to the reference mortar at the age of 7, 28 and 45 days were about 12% and 14%, 20% and 133% and 2% and 113%, respectively.

Similar significant improvement in compressive and flexural strengths in lime mixes containing ceramic-based powders like burnt bricks are reported in [11], due to the pozzolanic reactions and the filler effect of the materials causing a refinement of the pore system, improved ITZ and material bonding in the matrix.

The study results showed that prisms with fine-recycled-brick-aggregate mortar were about 24.5% stiffer than the stacks with natural-river-sand mortar (Table 5). With recycled-concrete-sand mortar, the modulus of elasticity was around 28.8% above prisms with natural-sand mortar. However, these differences appeared to be dependent on the strength of the masonry brick units and not the types of mortars. Nevertheless, the compressive strengths of the stacks with different sands were practically the same.

**Table 5.** Mechanical properties of reduced-scale walls (stacked prisms).

| Property | Unit | Stack Prism With Respect to Mortar Type | | |
|---|---|---|---|---|
| | | NSM | RCSM | RBSM |
| Compressive strength | MPa | 10.1 ± 1.51 | 10.4 ± 1.75 | 10.2 ± 0.47 |
| Modulus of elasticity | MPa | 1888 | 2431 | 2350 |

Note: Strength values are reported in the form of mean ± standard deviation (of three specimens). The modulus of elasticity is reported as the average of two determinations.

When compared to the previous study by Pelà et al. [42], the compressive strengths and the mean secant modulus of elasticity of stacks constructed from the same batch of bricks were different from the results obtained in this study. The compressive strength was nearly two times higher than the value reported in their work. The highest modulus of elasticity corresponded to the stacks with recycled-concrete-sand mortar and was about 424 MPa (17.4%) lower than the mean value reported in [42]. The differences might have been due to the differences in the thickness of bed mortars and in the size of the stacks, which meant a difference in slenderness ratio. The standard specifies a minimum of five courses, which was adopted in [42]. However, because of testing difficulties, only three-course two-joint prisms (Figure 8) were used in this study. Nevertheless, the findings agree with the results of the two-joint cylindrical cored samples reported in [42].



**Figure 8.** Reduced-scale wall prism.

## 4. Discussion

The study found that the mortar formed with recycled sands had lower density than the control mortar, but the density of the burnt-brick-sand mortar increased with age. While the lower density of the recycled-sands' mortars is known to be caused by the porosity of the materials, the increase in density of the burnt-brink-sand mortar can be attributed to the pozzolanic reaction between lime and the alumina and silicates of the burnt clay to form hydration products which densifies the matrix and improves the resulting properties. The water absorption of the mortars containing recycled sands was found to be higher than that of the control mortar and was maintained with age. The water absorption of the control mortar was found to decrease slightly with age. The similarity in water absorption of the recycled sands is due to the similarity in particle size distribution of the sands and the highly porous interfacial transition zones around particles of the recycled sands in the case of RCS and pores formed when crushing the bricks in the case of RBS.

On the other hand, the flexural and compressive strengths of the recycled-burnt-brick-sand mortar were higher than those of the recycled-concrete-sand and the control mortars.

The rate of strength development in this type of mortar was also higher compared to the latter two types of mortars. This phenomenon is believed to be a result of pozzolanic reactions taking place between the burnt-brick sand and the lime. The early strength development rate of the recycled-concrete-sand mortar was higher than that of the control mortar, but the final flexural and compressive strengths at the age of 45 days were the same. This can be attributed to the hydration of the non-hydrated cement from the adhered cement paste, which, however, was not examined in this study.

## 5. Conclusions

In this research, an experimental work on the use of recycled-fine-concrete and burnt-brick sands was conducted to examine the potential use of the recycled sands in hydraulic lime-based mortars for the conservation of historical buildings. Specifically, the mechanical and physical characteristics of the resulting mortars were studied. Based on the findings, the following conclusions can be drawn:

- Based on the table flow results, the workability of the RCSM and RBSM were similar and slightly higher than that of the reference mortar. Pre-soaking the recycled aggregates to the saturated-surface dry state, which increased the effective w/b ratio, is believed to increase the workability of the resulting mortars.
- Due to the porous nature of the aggregates, the bulk density of the RCSM and RBSM were lower than that of the NSM. The true or apparent density of the RBSM equalled that of the RCSM at the age of 7 days but was less than that of the reference mortar. After 28 days, due to pozzolanic reactions, i.e., the formation of hydration products, the RBSM became denser than the other two mixes.

The RCSM and RBSM had similar water absorption and porosity, which were higher than those of the reference mortar, NSM. This observation can be linked to the porosity of the recycled aggregate materials, which can be inferred from the water absorption capacity of the respective sands.

The flexural and compressive strengths of the RCSM and NSM were generally similar. Their slight improvement for the RCSM, particularly at the curing age of 28 days, can be attributed to the partial activity of the unreacted cement on recycled-concrete particles. After 28 days, both the flexural and compressive strengths of the RBSM were extremely high compared to those of the other two mixes, due to the pozzolanic reaction which might have occurred between the lime and the silicates and aluminates of the brick sands. Nonetheless, the 45-day strengths of both NSM and RCSM (ca. 1.3 MPa) were within the strength values reported earlier (1–6 MPa) for the characterised mortars in historical constructions.

The water absorption and porosity of all mortars were higher than that of the historical brick units. These characteristics are important for sacrificial materials like mortars as they indicate that water in the units can easily be drained out through the mortars enhancing the durability of the structure

The mechanical characteristics of the stacks (compressive strength and modulus of elasticity) were similar and appeared to be highly influenced by the properties of the brick units, regardless of the type of mortar.

Generally, all three types of mortars can be used for repair of historical buildings. Depending on the repair needs and the urgency to use the infrastructure, RCSM and NSM may work better for indoor repairs, e.g., plaster, and the use of RBSM can be extended to outdoor applications such as rendering and as bedding mortar.

Neither the partial replacement of materials nor the influence of pre-treating the recycled aggregates was examined in this study. In addition to the durability against

chemical attack and environmental exposure studies, future studies can explore these aspects, which may enhance the properties of the resulting historical repair mortars.

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